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Nano-fertilizers and nano-pesticides: A critical review of delivery mechanisms, environmental efficacy, and biosafety in sustainable crop production

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Abstract
Conventional chemical fertilizers and pesticides are used with poor efficiency: 40–70% of applied nitrogen, 80–90% of phosphorus, and 50–70% of potassium are lost to volatilization, leaching, and fixation, while more than 90% of sprayed pesticides fail to reach their target organism. These losses drive nutrient runoff, soil degradation, pesticide resistance, and biodiversity loss. Nanotechnology offers an alternative: nano-fertilizers and nano-pesticides (1–100 nm) that deliver active ingredients in a controlled, targeted, and often stimuli-responsive manner. This review synthesizes current evidence on the synthesis, classification, and plant-uptake mechanisms of nano-agrochemicals; evaluates their efficacy relative to conventional formulations; and critically examines the phytotoxicity, soil-microbiome, and regulatory concerns that currently constrain commercial adoption. We conclude that while nano-agrochemicals offer measurable gains in nutrient-use efficiency and pest-control precision, their large-scale deployment requires standardized biosafety testing and harmonized regulation before they can be considered a mature substitute for conventional inputs.

Keywords: Nanotechnology, nano-fertilizers, nano-pesticides, controlled release, nutrient use efficiency, phytotoxicity, sustainable agriculture

Introduction

The intensification of global agriculture over the past half-century relied heavily on conventional chemical fertilizers and pesticides. This drove the Green Revolution's productivity gains but at a mounting ecological cost. Conventional fertilizers exhibit poor nutrient-use efficiency (NUE): approximately 40–70% of applied nitrogen, 80–90% of phosphorus, and 50–70% of potassium are lost via volatilization, leaching, or soil fixation (Bindraban *et al.*, 2015) [1]. Similarly, over 90% of applied pesticides disperse into air, soil, and water rather than reaching the target pest, accelerating the emergence of resistant strains and non-target toxicity (Kah *et al.*, 2018) [7].

Nanotechnology — the engineering of materials at the 1–100 nm scale — offers a mechanistically distinct alternative. Nanoscale carriers possess a markedly higher surface-area-to-volume ratio than bulk formulations, which increases reactivity, improves cellular penetration, and enables more precise interaction with plant biological systems (Chhipa, 2017) [2]. Nano-fertilizers and nano-pesticides exploit this property to encapsulate, adsorb, or chemically bind nutrients or active ingredients onto nanocarriers, producing release profiles that can be tuned to match crop physiological demand or pest infestation cycles (Dimkpa & Bindraban, 2018) [3].

Classification and Synthesis of Nano-Agrochemicals

Nano-agrochemicals are classified by the composition of their nanomaterial matrix — principally metallic nanoparticles, metal oxides, carbon-based nanomaterials, and polymeric nanoconstructs.

a. Nano-fertilizers

Nano-fertilizers deliver macronutrients (N, P, K, Ca, Mg, S) or micronutrients (Fe, Zn, Mn, Cu, B, Mo) in three broad structural modalities:

1. Nanostructured materials, in which the nutrient itself is synthesized as a bioavailable nanoparticle (e.g., nano-urea, nano-ZnO, nano-hydroxyapatite for phosphorus).
2. Nanocoated additives, in which conventional granules are coated with a nanoscale film (carbon nanotubes, polymer hydrogels, clay minerals) that acts as a diffusion barrier and slows dissolution.
3. Nanomaterial carriers, in which nutrients are adsorbed, chemically bound, or encapsulated within porous host structures such as zeolites, mesoporous silica nanoparticles (MSNs), or chitosan nanoparticles.

Recent field-scale syntheses report that these formulations increase cereal yields by roughly 20–55% in wheat, 20–50% in maize, and 13–40% in rice relative to conventionally fertilized controls, though the magnitude is highly dependent on nanoparticle size, crystallinity, and application method (Ranjan *et al.*, 2025) [10]. Smaller, amorphous particles generally show higher NUE than larger, agglomerated or highly crystalline ones (Madlala *et al.*, 2024) [8].

b. Nano-pesticides

Nano-pesticides improve the stability and target efficacy of active agents against fungal pathogens, insect pests, and weeds. Common formulations include nano-emulsions, nano-suspensions, lipid nanoparticles, and polymeric nanocapsules, in which active ingredients such as permethrin, azadirachtin, or copper compounds are shielded from UV photodegradation and enzymatic hydrolysis in soil (Chhipa, 2017) [2]. A growing subset are stimuli-responsive, releasing their payload only on exposure to a defined pH, temperature, redox, or enzymatic trigger (Shen *et al.*, 2023) [12].

Table 1: Comparative matrix of common nanomaterials used in agriculture.

Nanomaterial	Primary Application	Mechanism of Action	Target Crops
Nano-urea / chitosan-N	Macronutrient delivery	Slow, controlled nitrogen release; reduces volatilization losses	Rice, wheat
Nano-hydroxyapatite	Phosphorus nutrition	Gradual orthophosphate release keyed to root exudate signals	Maize, soybean
ZnO nanoparticles	Micronutrient / antifungal	Enhances chlorophyll synthesis; induces oxidative stress in fungal pathogens	Tomato
Mesoporous silica (MSN)	Targeted pesticide carrier	Stimuli-responsive (pH/enzyme) release of encapsulated pesticide	Cotton
Polymeric nanocapsules	Herbicidal precision	Protects volatile active ingredients; enhances cuticular penetration	Cash crops / weed management

Mechanisms of Translocation and Cellular Uptake in Plants

The agronomic efficacy of nano-agrochemicals depends on their ability to cross plant structural barriers and reach target tissues without inflicting acute cellular damage.

a. Foliar uptake and translocation

Foliar-applied nanoparticles must first cross the cuticle, a hydrophobic wax layer, via either the stomatal or cuticular pathway. Open stomata have a size-exclusion limit of roughly 10–100 nm, allowing sufficiently small particles direct entry to the substomatal chamber. From there, particles cross the mesophyll plasma membrane by endocytosis, channel proteins, or carrier-mediated transport, then move symplastically through plasmodesmata into the phloem for systemic translocation to sink tissues such as roots, fruits, and apical meristems.

b. Root uptake and apoplastic/symplastic transport

Soil- or hydroponically applied nanoparticles must traverse the epidermis, cortex, and the suberized Casparian strip of the endodermis to reach the xylem. Transport occurs along cell walls and intercellular spaces (apoplastic route) or through cell interiors via plasmodesmata (symplastic route); the Casparian strip blocks apoplastic passage of larger particles, forcing a shift to the symplastic route at the endodermis. Particle size, surface charge, and functionalization jointly determine this transition efficiency, with smaller, positively charged particles translocating from root to shoot fastest.

Efficacy and Impact on Sustainable Agriculture

a. Enhancement of nutrient-use efficiency

Because nano-fertilizers release nutrients over an extended period rather than dissolving instantaneously, they can be tuned to more closely track crop uptake curves. Zeolite-functionalized nano-urea, for example, releases nitrogen at a rate that better matches real-time plant demand, which limits microbial conversion of surplus nitrogen to nitrous oxide (a potent greenhouse gas) and reduces nitrate leaching (Haydar *et al.*, 2024) [4]. Field-scale meta-analyses report NUE gains and yield increases in the range of 13–55% across major cereals, though outcomes vary substantially with nanoparticle formulation, dose, and crop (Ranjan *et al.*, 2025; Madlala *et al.*, 2024) [8, 10].

b. Precision plant protection and pest control

Conventional pesticide sprays degrade rapidly under solar radiation and are highly susceptible to wind drift. Stimuli-responsive nano-pesticides address this by releasing their active cargo only when a specific environmental or biological threshold is met — for instance, nanocapsules stable under neutral pH but that dissolve in the alkaline midgut (pH > 9) of chewing insects, or in response to enzymes secreted by fungal pathogens (Hu *et al.*, 2023). Metal-organic-framework (MOF) carriers have shown particular promise here, combining high porosity with tunable pH- or enzyme-responsiveness (Hu *et al.*, 2023). This specificity can lower the effective dose per hectare, reducing cost and sparing non-target organisms such as pollinators and earthworms.

Environmental Challenges, Phytotoxicity, and Biosafety

a. Phytotoxicity mechanisms

Accumulation of metallic and metal-oxide nanoparticles (Ag, CuO, and ZnO at elevated concentrations) within plant tissue can trigger intracellular overproduction of reactive oxygen species (ROS) such as hydrogen peroxide and superoxide radicals. Excess ROS causes lipid peroxidation of cell membranes, disrupts chloroplast thylakoid structure, and damages genomic DNA, manifesting phenotypically as chlorosis, stunted root elongation, reduced photosynthetic rate, and lower biomass accumulation. ROS-mediated oxidative stress is now recognized as the dominant mechanism underlying nanoparticle phytotoxicity across plant and microbial systems alike (Sharma *et al.*, 2023, as cited in the soil-microbiome literature discussed below).

b. Impact on soil microbiome and trophic transfer

Nanoparticles that wash into topsoil interact directly with the resident microbiome. Nitrogen-fixing bacteria (e.g., Rhizobium) and arbuscular mycorrhizal fungi are particularly sensitive: silver and copper nanoparticles disrupt bacterial membranes and inhibit enzymes central to nutrient cycling, and chronic ZnO exposure has been shown to damage Rhizobium morphology, delay nitrogen fixation, and induce early nodule senescence in legumes. Silver nanoparticles specifically have been linked to measurable reductions in microbial biomass and community diversity. There is also growing, though still limited, evidence of nanoparticle bioaccumulation in edible plant tissue (roots, grains, leaves), raising unresolved questions about trophic transfer into the human food chain that current research has not yet adequately addressed.

Comparative Assessment: Nano-Fertilizers versus Nano-Pesticides

Although both technologies exploit the same nanoscale delivery principles, they differ in risk profile and regulatory maturity. Nano-fertilizers generally use nutrient ions that are already biologically essential, so the primary concern is dose-dependent toxicity from over-accumulation rather than the introduction of a novel toxicant; their main limitation is inconsistent field performance across soil types and crop species, and yield benefits reported in the literature vary widely (13–55%) depending on formulation (Ranjan *et al.*, 2025) [10]. Nano-pesticides, by contrast, typically encapsulate compounds that are inherently biocidal, so encapsulation failure or premature release carries a higher acute ecotoxicological risk to non-target organisms; their advantage is a much larger design space for stimuli-responsive specificity, which nano-fertilizers cannot exploit as fully because nutrient release, unlike pesticide action, does not need to be pest-triggered.

Both classes share the same downstream uncertainty: neither has an internationally harmonized framework for long-term ecotoxicological testing, and both depend on nanocarrier materials (silica, chitosan, MOFs, metal oxides) whose environmental persistence is not yet fully characterized. Nano-pesticides are somewhat further ahead in mechanistic sophistication (MOF- and enzyme-responsive systems), while nano-fertilizers are closer to commercial-scale deployment, with products such as nano-urea already marketed in several countries.

Regulatory Frameworks and Future Directions

Commercial-scale adoption of nano-agrochemicals is constrained less by the underlying science than by the absence of harmonized regulation. Most jurisdictions still classify nanomaterials under bulk-chemical regulatory categories, despite nanoscale materials exhibiting distinct toxicological profiles, surface reactivities, and environmental fates. In the United States, oversight is split between the EPA (under the Toxic Substances Control Act) and the FDA, with no dedicated nanomaterial statute; the OECD has similarly called for harmonized, risk-based frameworks specific to nanoscale agrochemicals (Santos *et al.*, 2025) [11]. A comprehensive human-health risk-assessment framework for nanopesticides specifically has been proposed only recently (Kah *et al.*, 2021) [6], underscoring how young this regulatory science still is.

Looking forward, two directions appear most promising. First, green nanotechnology — biogenic synthesis using plant extracts or agricultural waste in place of toxic chemical reducing agents — offers a lower-risk production route. Second, integrating real-time biosensors with autonomous, stimuli-responsive delivery systems could enable genuinely closed-loop precision agriculture. Neither direction removes the need for standardized exposure thresholds, long-term environmental-fate tracking, and clear consumer labeling, which remain prerequisites for responsible scale-up.

Conclusion

Nano-fertilizers and nano-pesticides address a genuine and well-documented inefficiency in conventional agrochemical use, and the agronomic evidence for improved nutrient-use efficiency and pest-control precision is now substantial. However, the same nanoscale properties that improve efficacy — high reactivity and cellular penetration — are also the source of phytotoxicity and soil-microbiome risk. The technology's transition from laboratory and field trials to widespread commercial use will depend less on further gains in delivery efficiency and more on closing the current gaps in long-term biosafety data and regulatory harmonization.

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